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Viewing the circumnuclear medium "through" the radio absorption

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Abstract.

Observations of radio absorption (free-free and 21 cm neutral hydrogen absorption) can provide important constraints on the interstellar medium (either ionised or neutral) surrounding AGN. This gas is relevant in the obscuration of the central regions and, therefore, in producing the orientation-dependent aspects of the emission from the AGN itself, one of the key elements of the unified schemes. From these observations we can learn: how strong is the evidence for circumnuclear tori/disks and how often, instead, is the interaction between the radio plasma and large-scale ISM playing a role; are the tori/disks (when observed) thick or thin and how important is this gas in affecting the characteristics of radio sources, especially in their early phase. Here, I will summarise the recent results obtained from free-free and HI absorption observations of Seyfert and radio galaxies, what they can tell us about these issues, and which questions remain open.

1. Why Radio Absorption

Obscuration is one of the key ingredients for unified schemes of AGNs. The study of the nature of the foreground gas associated with AGN is therefore an important way to investigate the presence of obscuration and relate it to the predictions of the "standard" unified schemes. The study of this gas can be done at radio wavelengths in a number of ways and in this review I will concentrate on free-free absorption at GHz frequencies and on the 21-cm, hyperfine transition of atomic hydrogen, seen in absorption against a radio continuum source.

What can we learn from these observations that is relevant for unified schemes? The most interesting features to look for are the nuclear tori/disks. Following the original studies (e.g. Krolik & Begelman 1988), it has been often assumed that the nuclear tori are composed of dusty molecular clouds. It is now clear that, under certain conditions, these tori/disks can be, at least partly, formed by atomic hydrogen (Maloney et al. 1996). The torus will be molecular if its pressure exceeds a critical value that depends on the central source luminosity, the distance from the source and the attenuating column density between the central source and the point of interest in the torus. If the pressure is below this critical value, the gas is warm ($T \sim 10^4$ K) and atomic (Maloney 1998).

Atomic tori/disks can, therefore, be detected in absorption, against a strong radio continuum source (e.g. the core of the radio source), at the wavelength of the redshifted HI.

On the other hand, the inner edge of the torus is expected to be ionised by the intense radiation field from the central source. At the distance of the inner edge, likely between 0.3 pc and 1 pc from the AGN, a region of depth ~ 0.1 pc is fully ionised at a temperature of $\sim 10^4$ K and density $\text{few} \times 10^4 \text{ cm}^{-3}$. Such an ionised gas will radiate thermal emission and will cause free-free absorption of nuclear radio components viewed through the torus. This absorption is responsible for producing, at radio frequencies, a convex spectrum with a low-frequency cut-off.

In summary, both techniques can tell us about the presence of circumnuclear tori/disks and their characteristics (e.g. thickness). However, from the HI absorption we can learn more than that about the nuclear regions of AGNs. For example, whether gas outside the nuclear disk-structure can also be relevant for the obscuration of the AGN or whether kinematically disturbed gas is present, either in the form of *outflow* due to interaction of the radio plasma with the interstellar medium (ISM) or *infall*, due to gas possibly connected with the fuelling of the AGN.

2. Seyfert galaxies

2.1. Large HI disks

The most complete study of HI absorption in Seyfert galaxies has been done by Gallimore et al. (1999). They observed 13 galaxies and detected absorption in 9. Their main result is that no HI absorption is detected against the central, pc-scale, radio sources, even in known hidden Seyfert 1's like Mrk 3 or NGC 1068. In general, the absorption is detected against extended radio jet structures but appears to avoid central compact radio sources. The HI absorption appears to trace gas in rotating disks on the 100 pc-scale, aligned with the outer disks of the host galaxy, rather than gas associated with the very central (pc) regions of the AGNs. Indeed, there is a weak correlation between the probability to find HI absorption and the inclination of the host galaxy. Among the possible explanations for the result of Gallimore et al., is that free-free absorption suppresses the background source so that HI absorption cannot be detected.

A nice example of a galaxy showing a relatively large-scale disk is Mrk 231, studied in detail by Carilli et al. (1998) using the VLBA. There, a rotating disk with an east-west velocity gradient of about 110 km s^{-1} is observed. Also in this case the absorption is not toward the radio core on the pc scale but against a more diffuse radio continuum component seen on the hundred pc scale. The only galaxy that does not seem to follow this pattern is NGC 4151 that appears to be the only case of small scale torus, i.e. gas on the pc scale (Mundell et al. 1995). The column densities of the HI absorption inferred by Gallimore et al. (1999) are not correlated with those estimates from the X-ray absorption, but they are systematically lower (the mean column density from HI absorption is $\sim 10^{21} \text{ cm}^{-2}$ assuming a $T_{\text{spin}} = 100 \text{ K}$ while it is $\sim 10^{22.5} \text{ cm}^{-2}$ for the hydrogen column derived from soft X-ray). This is possibly indicating that the radio and the X-ray sources are not co-spatial.

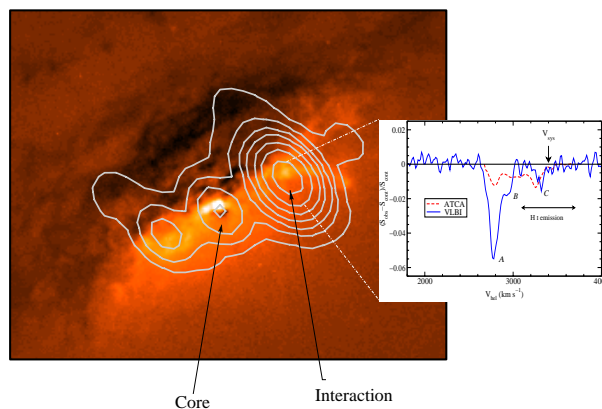


Figure 1. HST image of the central region of the Seyfert galaxy IC 5063 superimposed with the contours of the radio continuum (from the ATCA) showing the core and the two lobes. The spectra of the H I absorption (obtained with the VLBI and ATCA) against the strongest radio lobe show a blueshifted absorption, evidence of interaction of the radio plasma with the interstellar medium (Oosterloo et al. 2000)

Gallimore et al. (1999) found no evidence for major infall/outflow of neutral hydrogen. They concluded that in the Seyfert galaxies that they have studied, the atomic gas is mainly rotating. However, a clear case of broad H I absorption interpreted as outflow has been found in the Seyfert 2 galaxy IC 5063 (Morganti et al. 1998, Oosterloo et al. 2000). In this galaxy, highly blueshifted absorption ($\sim 700 \text{ km s}^{-1}$, see Fig. 1) has been observed. The absorption is against one of the radio lobes at about 2 kpc from the nucleus. In the same position, the kinematics of the ionised gas is also very disturbed and strong H₂ emission has been detected with NICMOS (Kulkarni et al. 1998) and interpreted as evidence for fast shocks. IC 5063 is one of the few Seyfert galaxies with a relatively strong radio continuum. Thus, similar absorption in other objects *even if present* could be difficult to detect because of the weaker radio continuum emission.

2.2. Evidence for free-free absorption

It has been clearly shown in the case of NGC 1068 (Gallimore et al. 1996, Roy et al. 1998) that the nuclear continuum source has been attenuated by free-free absorption. Indeed, thermal emission from the ionised edge of the accretion disk has been detected in this galaxy (Gallimore et al. 1997). Only one other candidate for detection of thermal emission (NGC 4388) has been found so far (Mundell et al. 2000). Possible signatures of free-free absorption due to the ionised inner part of the torus have been found in a number of Seyfert galaxies. Pedlar et al. (1998) report free-free absorption on scales $< 50 \text{ pc}$ in NGC 4151, while other cases of free-free absorption in Seyfert down to the scale of $\sim 1 \text{ pc}$ have been proposed by Wilson et al. (1998), Roy et al. (1998, 1999) and Ulvestad et al. 1999a. Two examples are shown in Fig. 2.

It is important to keep in mind, however, that distinguishing between free-free absorption and synchrotron self-absorption is not always straightforward.

The spectral shape that they produce is quite similar. Unlike free-free absorption, synchrotron self-absorption requires high brightness temperatures ($\sim 10^9$ K) due to the presence of a very compact source. Unfortunately, the brightness temperatures derived for the observed Seyfert galaxies are, in many cases, only a lower limit because the sources are still unresolved at the resolution of the available observations. Thus, with few exceptions, not all the data available so far are good enough to completely rule out synchrotron self-absorption as the cause of the observed absorbed spectra.

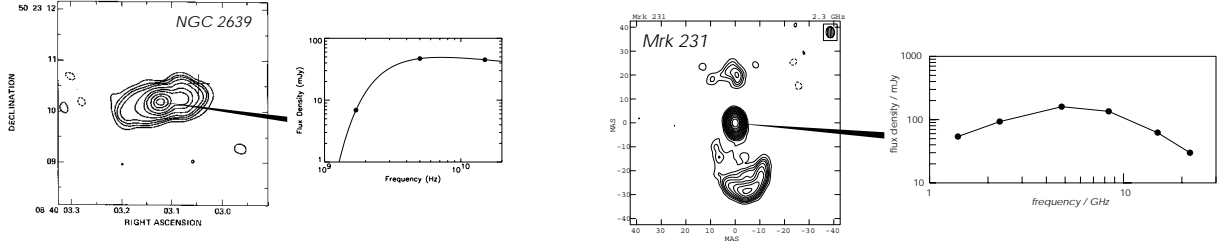


Figure 2. Two examples of absorbed spectrum in the Seyfert galaxy. *Left*, NGC 2639, VLA image from Ulvestad & Wilson and spectrum from Wilson et al. 1998 (left); Mrk 231 image at 13 cm and spectrum from Ulvestad et al. 1999b (right). Courtesy of Alan Roy.

Supporting the presence of free-free absorption in these objects is the absence of a counter-jet as observed in a number of Seyfert galaxies that nevertheless show symmetric radio emission on the larger scale. In these cases, Doppler boosting is unlikely to be the cause since the detected velocity of the jet is low (sub-relativistic, Roy et al. 1999). Another indirect argument in support of the free-free absorption interpretation, is that for a typical column density derived from photoelectric absorption in the X-ray, $\sim 10^{22.5-23} \text{ cm}^{-2}$, the corresponding densities ($\sim 10^5 \text{ cm}^{-3}$) are of the order of that required to produce free-free absorption (see e.g. Wilson et al. 1998).

3. Looking for nuclear tori/disks in radio galaxies

3.1. Tori/Disks in powerful radio galaxies

For powerful radio galaxies, geometrically thick tori are predicted by unified schemes. The combination of obscuration produced by tori/disks and beaming would explain the lack of broad optical emission lines in some of these galaxies. The main problem for the study of HI absorption in this group of sources is that their radio cores are, on average, not very strong. Because of this, there are only a few cases of extended powerful radio galaxies where HI absorption has been detected and a detailed study has been done.

Although extensive statistics are not available, in a recent study of a flux limited sample of radio galaxies, Morganti et al. (2001a) found that for FR type-II powerful radio galaxies, no HI absorption has been detected in the few broad

line galaxies observed, while three out of four narrow-line galaxies have been detected (the one non-detection having quite a high upper limit). To first order this is consistent with what expected according to the unified schemes assuming that the HI absorption is due to an obscuring torus. However, all the detected sources are compact or small radio galaxies. This result confirms what is found from previous studies (Conway 1997, van Gorkom et al. 1989) that powerful compact radio sources (i.e. powerful radio sources with a Fanaroff-Riley type-II morphology but on the scale of at most few kpc) are more likely to be detected in HI absorption. These kind of radio galaxies are likely to be good screens for detecting the absorption (Conway 1997), although it is not clear yet whether the high detection rate in these objects could also be due to the fact that they are believed to be young radio sources, and therefore likely to be embedded in a different (richer?) ISM.

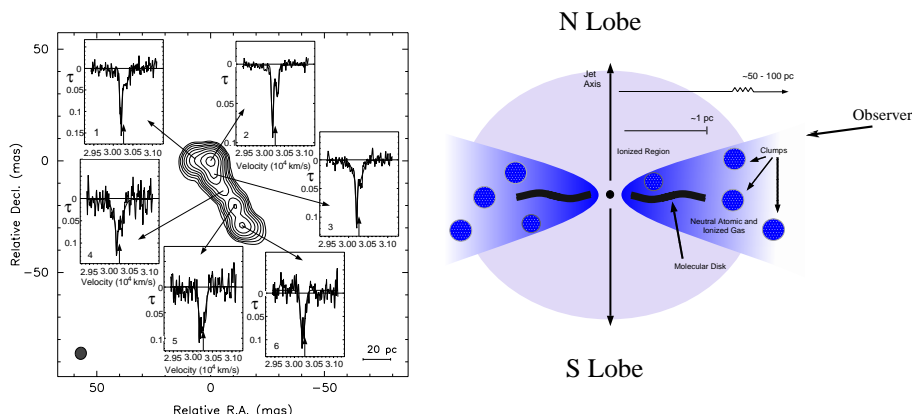


Figure 3. HI absorption profiles toward the radio source 1946+708 overlaid on the 1.3 GHz continuum contours Peck & Taylor 2001 (left). Line of sight to the jet components (right) in PKS 1946+708 (from Peck et al. 1999). Courtesy of Alison Peck and Greg Taylor.

There are a few cases of well studied radio galaxies that show in more detail evidence of the presence of tori/disks being the cause of the absorption. In the extended radio galaxy Cygnus A, broad absorption ($\sim 200 - 300 \text{ km s}^{-1}$) has been found against the nucleus by Conway & Blanco (1995). The large linewidth of the HI absorption is quite a common result in the detected radio galaxies, and it argues against the absorption arising at a large distance from the nucleus (i.e. kpc-scale). If it is gas at large radii, the expect absorption would be much narrower centred on the systemic velocity. From VLBA observation of Cygnus A, the HI gas seems to be distributed perpendicular to the radio axis and a velocity gradient is seen across this distribution. This suggests a 50 pc scale, rotating, flattened HI structure (Conway 1999). 4C 31.04 is a compact object where a sharp edge in opacity is observed in the western lobe while in the eastern lobe the opacity is quite uniform (Conway 1997). This has been taken as a signature of an almost edge-on torus/disk with thickness ~ 100 pc. HST observations of 4C 31.04 (Perlman et al. 2001) have confirmed the presence of a dust disk of the expected dimension as derived from the HI absorption. The

compact radio galaxy PKS 1946+708 (Peck et al. 1999, Peck & Taylor 2001) shows HI absorption visible toward the entire ~ 100 pc of the continuum source. Against the core the absorption is broader (~ 300 km s $^{-1}$) but with lower optical depth than against the rest of the source (see Fig. 3 and Peck & Taylor 2001 for details). According to Peck & Taylor (2001), this is in agreement with the thick torus scenario in which gas closer to the central engine rotates faster and is much hotter, thus lowering the optical depth. The narrow line is explained as coming from gas further out in the torus, possibly related to an extended region of higher gas density on the order of at least 80 - 100 pc in diameter. The column densities derived for the galaxies described above are $\sim 10^{23}$ cm $^{-2}$ if a $T_{\text{spin}} \sim 8000$ K is assumed. This value is what expected for purely atomic gas heated by hard X-ray emission. This is likely to be the condition close to the AGN. In this case, the column densities are consistent with what derived from the X-ray observations (one possible exception being 3C 445, Morganti et al. 2001).

Although most of the detected HI absorption in radio galaxies has been interpreted as evidence for nuclear tori/disks, there is a growing number of objects that cannot be explained in this way. As in the case of the Seyfert galaxy IC 5063 (see §2.1), there are radio galaxies where the HI absorption is associated with gas outflow due to jet-cloud interaction, see for example 3C 236 (Conway & Schilizzi 2001) and possibly PKS 1814-63 (Morganti et al. 2000). These cases will be discussed in §4.2. A caveat to the interpretation of the HI absorption, is the accuracy of the systemic velocity derived from the optical spectra. This is used as the reference velocity in the interpretation of the kinematics of the neutral gas. This will be discussed later in §4.1.

Fig.4 here

Figure 4. HI absorption detected with the WSRT and the VLA against the core of two radio galaxies: NGC 315 and B2 1322+36 (Morganti et al. in prep)

3.2. Thin disks in low power radio galaxies?

For low power radio galaxies (i.e. Fanaroff-Riley type I, FRI) the presence of a thick torus is not so clear yet. Using HST images, Chiaberge et al. (1999) found that unresolved optical cores are commonly present in these radio galaxies. The optical flux of these cores appears to be correlated with the radio core flux, arguing for a common non-thermal origin (synchrotron emission from the relativistic jet). All this suggests that the *standard pc-scale geometrically thick torus is not present in these low-luminosity radio galaxies* (see also Capetti et al. these proceedings) and the cores are, therefore, mostly unobscured.

In a study of HI absorption of a complete, flux limited, sample of FRI radio galaxies, Morganti et al. (2001a) found a low rate of detection. Only one of

the 10 FRI galaxies observed was detected in HI absorption. To first order, this result is consistent with the idea that the cores of these radio galaxies are relatively unobscured.

Recently, HI absorption has been studied in another sample of radio galaxies. For this sample, information from HST images about the presence of optical cores and nuclear dusty disks/lanes is available (Capetti et al. 2000, Capetti et al. these proceedings). Thus, the HI observations *aim to correlate the presence (or absence) of HI absorption with the optical characteristics*. Absorption was detected in the two galaxies in the sample (see Fig. 4) that have dust disks/lanes and *no* optical cores (B2 1322+36 and B2 1350+31 (3C293)). In these cases the column density of the absorption is quite high ($> 10^{21} \text{ cm}^{-2}$ for $T_{\text{spin}} = 100 \text{ K}$) and the derived optical extinction A_B (between 1 and 2 magnitudes) is such that it can, indeed, produce the obscuration of the optical cores. It is worth noticing that B2 1322+36 has a one sided jet on the VLBI scale. This is at variance with the idea (see Conway 2001) that HI absorption is mainly detected among the twin-jet sources that have also a counter jet. Two galaxies with optical cores were also detected (NGC 315 and B2 1346+26). In these cases, however, the derived column density is much lower ($\sim 10^{20} \text{ cm}^{-2}$ for $T_{\text{spin}} = 100 \text{ K}$) and the derived extinction is of the order of only a fraction of a magnitude. If the absence of large obscuration is confirmed for the low-power radio galaxies, the lack or weakness of broad optical lines compared to other AGN will have to be explained by something other than obscuration effects. So far, broad lines have been *tentatively* found in only a very few cases of low-power radio galaxies.

Fig.5 here

Figure 5. The background represent the HST image of NGC 4261. The inset are the VLBI images (from van Langevelde et al. 2000) of the nucleus at 21 cm (right) and the HI absorption spectrum observed slightly offset from the nucleus (left). Courtesy of Huib Jan van Langevelde.

Detailed studies of HI absorption using VLBI data have been done for few low-power radio galaxies. The best examples are NGC 4261 (van Langevelde et al. 2000) and Hydra A (Taylor 1996). In both cases, the evidence for a nuclear disk is based on the fact that the HI absorption is broad ($\sim 80 \text{ km s}^{-1}$). In Hydra A, the torus/disk could be quite edge-on (vertical extent $\sim 30 \text{ pc}$), consistent with the highly symmetric jets detected on the VLBI scale. In NGC 4261 the HI absorption is detected against the counter-jet (see Fig. 5, van Langevelde et al. 2000) at only 6 pc from the nucleus.

3.3. Free-free absorption in radio galaxies

Free-free absorption has been reported for a number of radio galaxies. A list of references for the galaxies studied so far can be found in Jones et al. 2000. Two

of the best studied objects are NGC 1275 (Walker et al. 2000) and NGC 4261 (Jones et al. 2000) for which multiple frequencies, high resolution images were obtained. In both cases, the free-free absorption is explained as due to an accretion disk. In the case of NGC 4261, an electron density (model dependent) in the inner 0.1 pc of the disk between 3×10^3 and 10^8 cm^{-3} is obtained while for NGC 1275 a value of at least $\sim 2 \times 10^4 \text{ cm}^{-3}$ if a thick medium (1 pc) is considered (therefore rising to higher values for a thinner medium).

A low frequency spectral turnover has been detected against the core and the inner part of the receding jet in PKS 1946+708 (Peck et al. 1999). This can be due to free-free absorption although, as in the case of Seyfert galaxies, synchrotron self-absorption cannot be completely ruled out. If the absorption corresponds to free-free, it could be part of an obscuring torus, likely the inner region of the same structure detected in HI absorption. A similar situation has been found in Hydra A where there is evidence (Taylor 1996) that the core and inner jets are free-free absorbed by ionised gas. According to Marr et al. 2001, strong evidence for free-free absorption are observed against the steep-spectrum lobes of the compact radio galaxy 0108+388, ruling out synchrotron self-absorption in this object.

Conway (2001) pointed out that all radio galaxies where free-free absorption has been detected show a parsec scale counter-jet as well as a jet. Moreover, the free-free absorption is concentrated against the counter-jet feature. This an indirect evidence that the detected free-free absorption, if confirmed, is likely to be the result of obscuration from an ionised disk oriented roughly perpendicular to the radio jet.

4. Alternative explanations for the HI absorption

4.1. Accurate redshifts & the HI in two star-bursting radio galaxies

An important issue for understanding the nature of the HI absorption is how the systemic velocity of the host galaxy compares with the velocity of the HI. It was already pointed out by Mirabel (1989) how the systemic velocities derived from optical emission lines can be both uncertain and biased by motions of the emitting gas. So far we have found two cases in which this problem clearly appears: the two compact radio galaxies PKS 1549-79 and 4C 12.50. In both cases, *two redshift systems* were found from the optical emission lines, thus making it difficult to define the “true” systemic velocity. In PKS 1549-79 and 4C 12.50 the higher ionisation lines (e.g. [OIII]5007Å) have a significant lower redshift (few hundred km s^{-1} difference) than the low ionisation lines (e.g. [OII]3727Å). *The velocity derived from the low ionisation lines is consistent with the one derived from the HI.* This is shown in Fig. 6 for 4C 12.50 where the velocities from the optical lines (Grandi 1977) are compared with the HI absorption recently obtained from the WSRT (this galaxy was already known to have HI absorption from the work of Mirabel 1989).

In the case of PKS 1549-79, the geometry derived from the radio morphology and the characteristics of the optical emission lines are not consistent with the prediction from unified schemes (see Tadhunter et al. 2001 for details). In this galaxy the high-ionisation lines are likely to form in a region close to

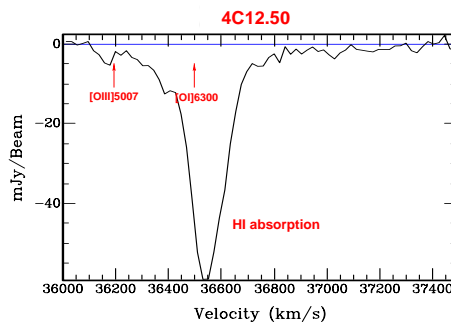


Figure 6. HI absorption of 4C 12.50 observed with the WSRT. The velocity derived from the optical emission lines ([OIII]500Å and [OII]3727Å from Grandi 1977) are marked.

the central AGN, which is undergoing outflow because of interactions with the radio jet, while the low-ionisation lines and the HI absorption come from an obscuring region at a larger distance from the nucleus and thus not so disturbed kinematically. PKS 1549–79, as well as 4C 12.50, are likely to be *young* sources where the nucleus is surrounded by a cocoon of material left over from the events which triggered the nuclear activity. Indeed, they are luminous far-IR sources (4C 12.50 is even classified as ultra-luminous and it is also rich in CO, Evans et al. 1999) and they have a strong spectral component from a young stellar population.

The possibility that the rich medium around a radio galaxy could be responsible for both the HI absorption as well as being related to the young stellar population component is supported by the fact that the fraction of radio galaxies with young stellar population that are detected in HI seems to be particularly large (so far *all* have been detected) suggesting a link between the two effects (Morganti et al. 2001a,b). The starburst component and the cocoon of absorbing material around the radio lobes can also affect the way we see (and classify) the AGN, especially at optical wavelengths. This may be the case in PKS 1549–79. This has been recently pointed out also by the work of Levenson et al. (2001) for example in the case of the Starburst/Seyfert-1 galaxy NGC 6221.

A major implication of these results is that the simplest version of the unified schemes may not always hold for young, compact radio sources.

4.2. Infall and outflow

In previous studies, the HI absorption was mainly found either at the systemic velocity or redshifted compared to it (van Gorkom et al. 1990). As a result of a number of recent studies, both redshifted and blueshifted (with respect to the systemic velocity) cases of HI absorption have been found. However, it is clear from the above discussion that, in general, accurate redshifts are needed before we are able to be sure of the interpretation. At present, there are only a few cases of clearly redshifted HI absorption. One of these cases is NGC 315. The well known deep and very narrow component (Dressel et al. 1983) 500 km s^{−1} redshifted compared to the systemic velocity, is clearly visible in Fig. 4. A

similar double HI absorption has been found in 4C 31.04. These are probably the only two examples, so far, where we are detecting an infalling cloud that could be physically associated with the nuclear region (although the case of NGC 315 is not yet compelling). Thus, this would represent a cloud close to the nucleus, falling into it and "feeding" the AGN.

In some cases, the HI absorption seems to come from gas situated around the radio lobes and affected by the interaction with the radio plasma (i.e. out-flow). The best example is the Seyfert galaxy IC 5063 (described in §2.1). Among the radio galaxies, evidence of jet-cloud interaction affecting the HI absorption has been found in 3C 236 (Conway & Schilizzi 2000). In this galaxy the atomic absorption is associated only with the eastern lobe of the central 2 kpc mini-double structure. An other possible example is the compact radio galaxy PKS 1814-63. In this galaxy the HI absorption is observed against the entire radio emission (~ 350 pc, Morganti et al. 2000). Most of the HI absorption (with an optical depth as deep as 30%) is blueshifted compared to the systemic velocity of the galaxy (at least if we rely on the redshift available so far). Thus, this component could be associated with extended gas, possibly surrounding the lobes and perhaps interacting/expanding with them. The superluminal object 3C 216 could be an other example (Pihlström et al. 1999). A few more galaxies where the derived velocity of the HI absorption is blueshifted compared to the systemic velocity have been found, although more accurate data are still needed to confirm them.

5. Summary

Observations of HI absorption in both Seyfert and radio galaxies appear to tell us more about the 100-pc scale nuclear disks than about the pc-scale tori. In Seyfert galaxies, the 100-pc scale rotating disks traced by the HI absorption are aligned with the outer disks of the host galaxy. Only one case of absorption on parsec scales has been found. The nuclear continuum source is believed to be attenuated by free-free absorption, and signatures of this have been found in the spectra of a number of Seyfert galaxies, as well as in the lack of a counter-jet in objects where a sub-relativistic velocity of the jet has been measured. However, synchrotron self-absorption as a possible alternative explanation for the absorbed spectra cannot, in many cases, be completely ruled out yet.

Evidence for tori on the 100 pc scale has also been found in a handful of radio galaxies from VLBI studies. Only one object shows the absorption against the counter-jet at a projected distance of 6 pc. The low detection rate of HI absorption in low-luminosity radio galaxies, as found from statistical studies, appears to be consistent with thin nuclear disks being characteristic of this class of radio galaxy. In radio galaxies, free-free absorption has been also observed and all the detected objects show a parsec scale counter-jet (as well as a jet) and the free-free absorption is concentrated against the counter-jet feature. Thus, also in these objects the free-free absorption is likely to be the result of obscuration by an ionised disk oriented roughly perpendicular to the radio jet.

Despite these results, it is fair to say that the evidence is sometimes circumstantial and more objects need to be studied. Indeed, among both Seyfert and radio galaxies, there are numerous examples where the HI absorption traces

gas that is not distributed in a disk but is surrounding the radio lobes and interacting with them (outflow). In a few cases, this represents clouds falling into the nucleus. It is therefore extremely important to obtain accurate systemic redshifts for a correct interpretation of the HI absorption.

Finally, the obscuration by a cocoon of gas surrounding the radio lobes observed some radio galaxies may alter the observed characteristics of the radio source, making the classification according to the unified schemes more complicated .

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